

The Fate of Ultra-Luminous Mergers

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Abstract

Essentially all Ultra-Luminous IR Galaxies (ULIRGs) are in disturbed, interacting or merging systems. It is known that interactions tend to induce galactic starbursts. Thus, elliptical galaxies which are formed in mergers will tend to have high metallicity, low dust and molecular gas content, and faint structural distortions, as observed for the *bone fide* elliptical galaxy population. The old stellar population in the merged galaxies will probe the new gravitational potential, relaxing rapidly to give a de Vaucouleurs surface-brightness profile if the remnant is elliptical-like. We examine the old stellar population in 10 nearby¹ ($z < 0.15$) ULIRGs, using deep near-IR imaging photometry. These data reveal signs of elliptical-like structure in the near-IR one-dimensional surface brightness profiles, supporting the hypothesis that ultra-luminous mergers evolve into elliptical galaxies.

1 Motivation : Mergers and Galaxy Formation

The fundamental question underpinning this study is : ‘What astrophysical processes determine whether a galaxy forms as a disk or an elliptical system?’ It is now clear that galaxy formation is not an unique event which occurs in the early universe, but rather, a diverse range of processes which are ongoing even to the present epoch. Numerical simulations [1] suggest that collisions between disk galaxies form systems which pass through a massive burst of star formation, and eventually produce ‘elliptical-like’ remnants with mass distributions similar to those inferred for *bone fide* elliptical galaxies. Toomre [2] showed that the observed relative numbers of merging systems and elliptical galaxies are consistent with a significant fraction of ellipticals forming *via* the merging of spiral galaxies, an ironic inversion of Hubble’s original sequence. Theories of galaxy formation divide into ‘top-down’ and ‘bottom-up’ scenarios. The merging of smaller

¹In this paper, we assume $q_0 = \frac{1}{2}$ and H_0 as stated.

disk galaxies to form massive spheroidal galaxies fits well with the bottom-up ‘hierarchical clustering’ galaxy formation schemes envisaged in cosmologies where cold, dark mass dominates the Universe. It is therefore plausible that some ultra-luminous mergers are ‘factories’ turning molecular gas-rich, dusty disk galaxies into elliptical-like systems. In order to advance an observational study of the rôle of disk-disk mergers in the formation of elliptical galaxies, a sample of galaxy systems in the process of merging is needed.

Observationally, luminous far-IR (FIR) emission is known to trace star formation [3]. The *ultra*-luminous IR galaxies (ULIRGs) are almost all disturbed, interacting or merging systems (Clements and co-workers [4, 5]). ULIRGs are distinguished by $L_{\text{bol}} \sim L_{\text{FIR}} = 10^{12} L_{\odot}$ ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), which means that they are amongst the most luminous galaxies in the Universe. The prodigious far-infrared (FIR) emission from ULIRGs appears to be triggered by the interaction and merger of galaxies, and produced by very warm dust. It seems clear that for the vast majority of the population of luminous IR galaxies, the dust is heated by emission from regions of star formation. However, in the most luminous systems, there is often also evidence of an active nucleus, producing Seyfert-like high-ionization emission lines with velocity widths much greater than those of normal galaxies [3, 4]. An excellent review of luminous IR galaxies has been given by Sanders and Mirabel [3].

It is clear that ULIRGs represent an easily-identifiable sample of galaxy mergers, and are ideal for the present purpose.

2 The Infrared Imaging Data

For this study, we selected ULIRGs from the literature [6, 7, 8] by two main criteria. We required targets which are sufficiently nearby (redshifts $z < 0.15$) for good spatial resolution, and which are all confirmed as interacting and merging systems by previous observations. The basic characteristics of the sample are given in Table 3. One ULIRG in our sample, IRAS 16487+5447 had been classified as ‘isolated and undisturbed’ based upon optical imaging [6]. However, our near-IR data revealed an unambiguous double nucleus. The evidence that essentially all ULIRGs are in disturbed, interacting or merging systems is now becoming overwhelming [3, 5].

The aim of the current project is to use the old stellar population as test particles to probe the gravitational potential resulting from galaxy interaction and merger. The integrated emission contributed by the pre-existing old, red stars, relative to the young, blue burst stars, is much greater in the near-IR than at optical wavelengths. Therefore, we obtained deep K-band images of the 10 ULIRGs using the Blue MAGIC infrared camera on the Calar Alto 3.5m telescope. Our data have a spatial scale of $0.32''/\text{pixel}$, so the field-of-view is $82'' \times 82''$, which is roughly equivalent to 10 – 20 effective radii (r_{eff}) for the target galaxies. The exact physical scale is given by the standard formula [9] $l = l(z, \phi, h_{100}) = 29.07 \frac{\phi''}{h_{100}} f(z)$ where $f(z) = (1+z)^{-2} \left[(1+z) - (1+z)^{\frac{1}{2}} \right]$ depending upon the redshift z , the angular separation ϕ in arcseconds and the Hubble parameter $H_0 = 100 h_{100} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

We used the narrower K-band filter, Km (based on that described by Wainscoat and Cowie [10]), since this reduces the contribution of thermal sky emission to the background flux. The exposures were taken in a dithered pattern, with total integration times in the range 1000 – 2700 s per ULIRG. Therefore, the sensitivity of our data reaches $\sim 20.5 \text{ mag arcsec}^{-1}$. The seeing was generally good, being typically $< 1''$, with a few poorer intervals.

The data were reduced using the IRAF packages² and standard techniques. We made

²IRAF is distributed by the NOAO, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

measurements of photometric reference stars throughout the observing run. However, there were problems with absolute photometric calibration due to the defocusing used to prevent the standards from saturating the MAGIC detector. The photometric calibrations have been verified by comparison with previous published aperture photometry of Arp 220 [11].

3 Surface Brightness Profiles

One straight-forward discriminator between elliptical and disk galaxies is the shape of the azimuthally-averaged surface brightness profile. As a first step in determining the fate of the ultra-luminous mergers in our sample, we have examined these one-dimensional surface-brightness profiles. The profiles were calculated by averaging the flux in elliptical annuli using the IRAF `ellipse` routine. We then fit analytic surface brightness profiles of the form

$$\propto \exp \left[- \left(\frac{r}{r_s} \right)^\beta \right] \begin{cases} \beta = 1 & \text{disk} \\ \beta = 0.25 & \text{elliptical} \end{cases}$$

The shape parameter β takes a value $\beta = 1$ in disk galaxies (the exponential disk profile), and $\beta = \frac{1}{4}$ in elliptical galaxies (the de Vaucouleurs $r^{\frac{1}{4}}$ law). In principle, the value of β could depart from the shape of these traditional spiral and elliptical galaxy structures. We therefore calculated fits in which β was unconstrained, but these did not result in a significantly better description of our data.

We use the standard χ^2 ‘goodness-of-fit’ parameter to choose between the possible descriptions of the distribution of the infrared light in the ULIRGs in our sample. A potential problem with this approach is that we are interested in the *overall* distribution of the old stellar population, whereas the χ^2 parameter is sensitive to all the detailed structure down to the spatial resolution of the data. Therefore, we do not expect to obtain fits such that $\chi^2 = 1$ per degree of freedom. Still, a lower value of χ^2 still means that the differences between the data and the model are reduced. We therefore use the ratio between the values of the χ^2 parameter for the disk and elliptical description of each galaxy to decide which is our *preferred* description in each case. A more refined approach could use the colours of each galaxy to identify and hence mask out of the fit those regions which are not dominated by old stellar light.

The results are given in Table 3. In 8 of our 10 systems, we strongly favour the elliptical-like description. For 15327+2340, we cannot discriminate between the two descriptions using our current approach. For the remaining, ULIRG 00015+4937, we clearly favour the disk-like description. This is a clear double nucleus system, and the data given are for the brighter of the two nuclei. Judging by the large separation of the nuclei in this case, the merger is at a relatively early stage. We are therefore detecting the pre-existing galaxy structure of what is probably a molecular gas-rich spiral.

4 Arp 220

As an oft-cited example of a ‘prototypical’ ULIRG, it is to be expected that the results for Arp 220 will be unusual in any study of the ULIRG population. The fierce debate over the energy budget of Arp 220 is ongoing. New evidence has emerged to support the hypothesis that the bulk of the FIR emission is fuelled by a massive starburst [13]. However, the hypothesis that a hidden AGN is the dominant power-source is also well-supported. For example, new mid-IR spectrophotometry indicates that the heating source for the dust is smaller than a few

IRAS name of ULIRG	Alternative Name(s)	Redshift ¹ z	χ^2 ratio
00015+4937		0.148	5.8
15250+3609	PGC 055114	0.0554	0.92
15327+2340	Arp 220	0.01813	0.05
16487+5447		0.1044	0.52
17179+5445		0.1475	0.38
17208−0014	PGC 060189	0.04281	0.32
19297−0406		0.08573	0.42
20414−1651		0.08708	0.17
20087−0308		0.10567	0.16
22491−1808	PGC 069877	0.07776	0.09

Table 1: Information about the Ultra-Luminous IR Galaxies.

¹ Redshift data are taken from the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

parsecs [14] . It seems increasingly likely that Arp 220 is a hybrid system, with significant energy contributions from both an active nucleus and star formation activity.

Previous work on Arp 220 by Wright et al. [12] used data taken in relatively poor seeing ($\sim 2''$) and with a spatial resolution ($0.62''/\text{pixel}$), half that of the present study. They determined that Arp 220 is an elliptical-like system ($\beta = \frac{1}{4}$) with an effective radius $r_{\text{eff}} = 3.8\text{kpc}$. Our new results confirm that the overall structure of Arp 220 is elliptical-like, although we find a somewhat smaller effective radius of $r_{\text{eff}} = 2.4\text{kpc}$, consistent with our better seeing and spatial resolution. The data and model for the surface brightness profile of Arp 220 are shown in Figure 4.

5 The Fate of Ultra-Luminous Mergers

The one-dimensional surface-brightness profiles of these ULIRGs show a strong tendency to be better described by a de Vaucouleurs $r^{\frac{1}{4}}$ law than by an exponential disk. This is the case for 8 of the 10 systems in the present study. We infer that ultra-luminous mergers can process (disk) systems which are rich in molecular gas, eventually relaxing into (molecular gas-depleted) elliptical-like systems. This is yet another indication that many ‘normal’ galaxies are far from serene. Our results support the suggestion that the collision and merger of classical spiral galaxies can produce classical elliptical galaxies, through astrophysical processes such as tidal disruption, violent star formation accompanied by prodigious infrared emission, and gravitational relaxation.

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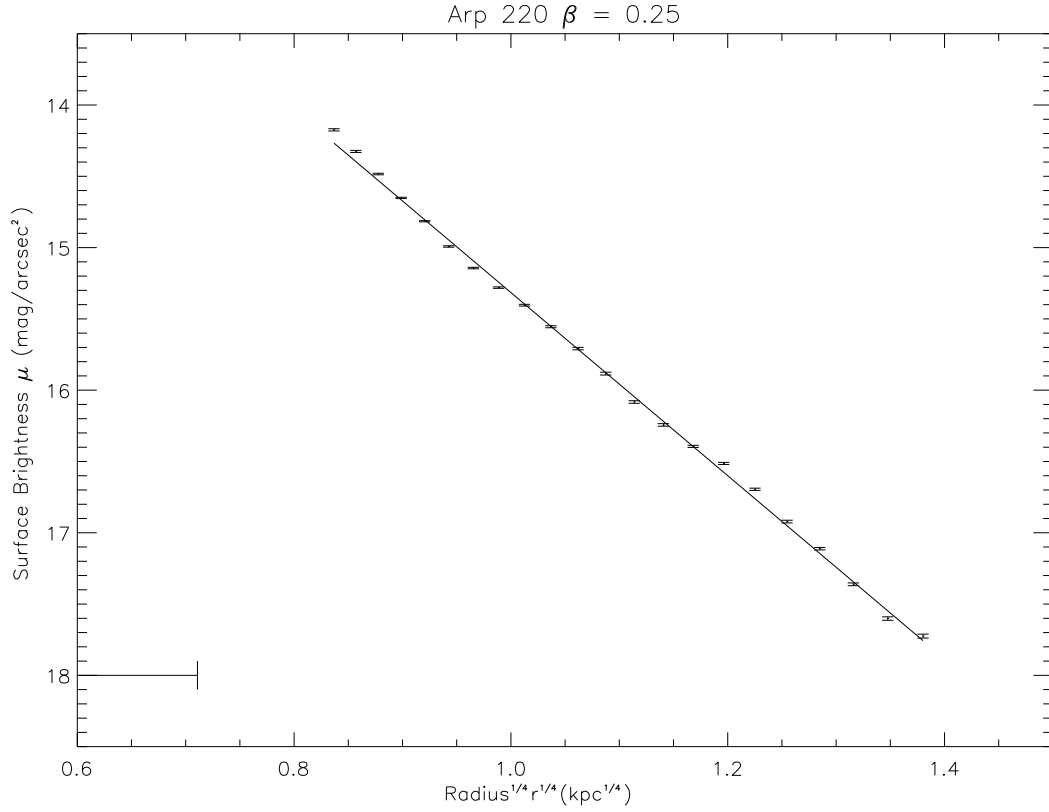


Figure 1: The Surface Brightness Profile of Arp 220

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